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HH 46/47: Also a parsec scale flow ⋆

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Abstract. We report the discovery of a pair of large Herbig-Haro type structures roughly 10 arcminutes (1.3 pc) north-east and south-west of the source driving the well-known HH 46/47 Herbig-Haro jet in new deep emission-line images made using the Wide Field Imager on the ESO/MPG La Silla 2.2-m telescope. These new images suggest that the HH 46/47 outflow is much more extensive than previously assumed, extending over a total of 2.6 pc on the sky, or over 3 pc in space, when deprojected. HH 46/47 thus also belongs to the recently-discovered class of giant Herbig-Haro flows.

Key words: ISM: jets and outflows – Stars: formation – ISM: individual: HH 46/47

1. Introduction

Observations over the past few years with large sensitive imaging cameras have shown that outflows and jets from young stars often extend over several parsecs, much further than previously suspected. Examples of these giant flows include well-known jets such as HH 34, HH 24, HH 111, HH 1/2, and the flow from T Tau (e.g. Bally & Devine 1994, 1997; Devine et al. 1997; Eislöffel & Mundt 1997; Reipurth et al. 1997, 1998b). The discovery that such outflows can be so large has significant implications for our understanding of their lifetimes and the cumulative impact they may have on their natal molecular clouds.

HH 46/47 is a well-studied prototypical Herbig-Haro jet located in the Gum Nebula, driven by a young source (HH 47 IRS or IRAS 08242−5050; Graham & Elias 1983; Emerson et al. 1984; Cohen et al. 1984; Graham & Heyer 1989, Reipurth & Heathcote 1991) embedded in a southern Bok globule (GDC 1 = ESO 210−6A; Bok 1978; Reipurth 1983). The two brightest components of this outflow system, HH 46 and HH 47, were discovered by Schwartz (1977), and shown by Dopita et al. (1982; see also Graham & Elias 1983) to be shock-excited HH objects in a collimated bipolar flow. The blue-shifted lobe of the flow, with main components HH 46, HH 47 A, and HH 47 D, is prominent in optical emission as it escapes the globule, whereas the red-shifted lobe is mostly hidden from view as it runs through the globule, only to become visible again in the guise of HH 47 C as it leaves the globule; H_2 emission from the jet as it traverses the globule can however be seen in the near-infrared (Eislöffel et al. 1994). From HH 47 D in the north-east to HH 47 C in the south-west, the flow was thought to extend over 0.57 pc in projection at a distance of $\sim$ 450 pc.

Ground-based optical imaging has been presented by Bok (1978), Reipurth & Heathcote (1991), Hartigan et al. 1993, Eislöffel & Mundt (1994), and Morse et al. (1994) among others, while HST images have been presented by Heathcote et al. (1996). A characteristic feature of the HH 46/47 jet is the apparent change in flow direction with time, from small-scale wiggles seen in the HST images (Heathcote et al. 1996) to a more gradual turning towards smaller position angles (Reipurth & Heathcote 1991). There is also an obvious misalignment of $\sim$17° between the jet and the counterjet seen near the driving source (Reipurth & Heathcote 1991).

Morse et al. (1994) found that the outermost bowshock, HH 47 D, is running into previously accelerated material and they presented an image showing an Hα feature 50 arcsec ahead of HH 47 D, which they suggested showed that HH 46/47 extends over a greater length than previously known. In this paper, we report the discovery of two groups of Herbig-Haro type objects at distances of approximately 10 arcmin (1.3 pc) to the north-east and south-west of HH 47 IRS and as a result, we argue that the HH 46/47 flow is indeed much larger than previously suspected, extending over several parsecs at least.

2. Observations and data reduction

The images presented here were taken with the Wide Field Imager on the MPG/ESO 2.2 m telescope on La Silla on Jan. 21 1999. The camera uses a mosaic of 8 CCDs, each a 2k$\times$4k pixel array, providing a total detector size of 8k$\times$8k pixels with a field-of-view of $\sim$0.54$\times$0.54 degrees at an image scale of 0.25 arcsec/pixel. Images were taken through narrow-band filters at 658 nm (Hα) and 676 nm ([S II]), and a medium-passband filter at 753 nm, which was used to measure continuum emission. Integration times were 20 min (Hα), 30 min ([S II]), and 12.5 min (continuum), each split into 5 dithered exposures to compensate for the gaps between the CCDs, bad pixels, and cosmics.

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Fig. 1. Narrow-band 658 nm (Hα+continuum) image of the area around GDC 1, the globule harbouring the HH 46/47 energy source, HH 47 IRS (position marked by the cross). The image covers $21' \times 14'$, i.e. $\sim$2.7 pc $\times$1.8 pc at a distance of 450 pc. The globules GDC 1 and 2 are seen as opaque, dark features with bright rims at their north-western edges. Several smaller, less opaque globules are outlined by bright rims, including a very narrow, transparent fingerlike structure. In addition to the overall diffuse Hα emission from the Gum Nebula, compact structures are seen, namely the known HH 46/47 jet complex originating in GDC 1 and the newly discovered HH objects (marked by arrows).

Fig. 2. Continuum subtracted Hα image of the same area as in Fig. 1. The major features in the HH 46/47 jet are labeled. The feature ahead of HH 47 D found by Morse et al. (1994) is also seen. The newly discovered HH objects are labeled as HH 47 NE and HH 47 SW. While HH 47 NE seems to form a large bow shock, the morphology of HH 47 SW is not well defined.

Data reduction was standard, starting with bias frame subtraction and division by a flat field frame (a combination of dome and sky flats); bad pixels were masked and excluded from further processing. Then mosaics were made from the single exposures as follows. First, a "positional reference frame" was constructed from the continuum exposures by accurately registering and combining the data for each chip separately, resulting in one average image for each chip. Large enough dithering steps had been chosen such that these images overlapped, allowing an accurate determination of the position of each chip with respect to the others. The averaged images for each of the 8 chips were then registered, rotated, shifted, and finally averaged into one large master image which served as positional reference frame for registering the other exposures. All individual exposures through all three filters were then registered to this positional reference frame. The final mosaics were then constructed by taking the median of the rotated and shifted single exposures to reject cosmic ray events.

Further processing of the Hα image was applied to show the newly discovered HH objects more clearly. The Hα frame was lightly gaussian smoothed so that the PSF matched that of the continuum frame; the latter was then appropriately scaled and subtracted from the Hα image. Since the wavelength difference between two filters was quite large, different colours of stars led to many small residual images which were removed by hand. Finally, a large-scale NW-SE gradient in the Hα emission was subtracted from the image to enhance the contrast.

3. Results

Figure 1 shows a $21' \times 14'$ ($\sim$2.7 pc $\times$ 1.8 pc) section of the Hα image. The position of the young star driving the HH 46/47 flow (the only protostellar object known in the area) is marked by a cross. It is seen to be embedded in a globule (GDC 1) which is illuminated and evaporated from the north-west by the exciting stars of the Gum nebula H II region ζ Pup and γ^2 Vel several degrees (20-40 pc) to the north-west. In the south-eastern part of the image, a number of apparently connected illuminated globules, rims, and fingerlike structures can be seen: these may be the remains of a larger cloud that has been evaporated from the north-west. The edges of these globules are outlined by rims of Hα emission. Smooth extended Hα emission is seen to fill the spaces between the globules and to the north-west. The HH 46/47 jet system consists of much more compact, knotty, and filamentary Hα structures. Superimposed on the smooth background, a number of additional compact, knotty patches of Hα emission can also be seen in the north-eastern and south-western corners of the image (marked with arrows).

Figure 2 shows the same field with the continuum emission and large-scale Hα gradient subtracted in order to show the compact Hα features better. The main features are the rims around the globules whose structure suggests illumination from the north-west, with bright emission at their north-eastern tips and streamers extending to the south-east. In addition to GDC 1 harbouring HH 47 IRS and a comparably-sized second globule, GDC 2, at the eastern edge of the image (Reipurth 1983), many smaller and less pronounced features are seen, including a very narrow finger pointing to the north-west.

The features in the north-east and south-west corners marked by arrows in Fig. 1 also stand out clearly now. We argue that these are Herbig-Haro type structures as follows:

– The knots are emission line features, detected in Hα and in [S II] (albeit only faintly in the latter line), typical of Herbig-Haro objects;
– They display a much more compact structure than the emission from the background H II region, suggesting emission from shocked gas rather than from the diffuse ionized gas;
– Their morphology differs from that of the rims around the globules: the latter are indicative of thin layers of gas evaporating from the denser globules, wrapping around the globules, while the candidate HH objects show up as compact blobs unassociated with any globules; the north-eastern group forms a bow-like structure heading north-east, whereas the rims around the globules head north-west;
– The morphology of the north-eastern group is reminiscent of a large fragmented bow shock, indicating a working surface in a flow heading north-east, pointing back to somewhere in the vicinity of HH 47 IRS;
– The south-western group is at the same distance from HH 47 IRS as the north-eastern group, suggesting that these may be matching shocks in a single flow, created by the same ejection event.

We will henceforth refer to the north-eastern and south-western groups of knots as HH 47 NE and HH 47 SW respectively. The approximate location of HH 47 NE is 8^h 26^m 40^s, $-50°$ $58'$ $15''$ (J2000), some 9.9 arcmin ($\sim$1.3 pc) from HH 47 IRS at a position angle of $\sim$74°. HH 47 SW is at roughly $8^h\ 24^m\ 55^s$, $-51°\ 07'\ 00''$ (J2000), 10.5 arcmin from HH 47 IRS at a position angle of $\sim$50°.

The discovery of these HH objects suggests that the previously known HH 46/47 jet is only the innermost portion of a much larger flow, as suggested by Morse et al. (1994) based on their analysis of the HH 47 D bow shock. The flow is now seen to extend over at least $\sim$2.6 pc in projection, or $\sim$3 pc when deprojected using an orientation of $\sim$30° out of the plane of the sky (see Eislöffel & Mundt 1994; however, we do not know if and how the flow direction changes with respect to the plane of the sky). Thus HH 46/47 can be added to the growing class of parsec-scale outflows from young low-mass stars. Assuming a tangential flow velocity of about 150 km/s (see, e.g. Reipurth & Heathcote 1991; Schwartz et al. 1984; Eislöffel & Mundt 1994; Micono et al. 1998), the dynamical timescale for the new outer bow shocks HH 47 NE and SW is about 9000 years.

HH 47 NE is displaced from the current jet axis (as defined by the north-eastern lobe of HH 46/47 with respect to HH 47 IRS, at a position angle of $\sim$54°) by about 20°. However, Reipurth & Heathcote (1991) found that, in addition to short timescale kinks and wiggles, the north-eastern lobe of the HH 46/47 jet appears to have been gradually changing its flow direction towards smaller position angles, by about 3° from HH 47 D to HH 47 B. The time between the ejection of these features is estimated to be about 1300 years; extrapolating this over the 9000 year dynamical timescale of HH 47 NE yields a change in flow direction of about 21°. Thus, the observed displacement of HH 47 NE from the current flow axis is consistent with a steady change of flow direction over the last 9000 years at the rate currently observed for the inner part of the jet.

While HH 47 SW is only a few degrees off the current axis of the flow as defined by the north-eastern lobe of the inner HH 46/47 jet, it lies some 8° off the axis of the south-western lobe (PA$\sim$58°), as defined by HH 47 C and the counterjet seen near the source in [S II] and H_2. This also indicates a gradual change in flow direction in the south-western lobe, albeit smaller than seen in the north-eastern lobe.

The different position angles of HH 47 NE and SW also indicate that the flow directions of the north-eastern and south-western lobe were not coincident at the time HH 47 NE and SW were ejected. This is consistent with the observation that the previously known inner jet and counterjet are not aligned at their origin (Reipurth & Heathcote 1991). The newly discovered binary nature of the outflow source (Reipurth, pers. comm.) may hold the key to understanding the wiggles, bends, and misalignment of the HH 46/47 jet and counterjet.

HH 47 NE and SW are rather faint in the [S II] filter, making it difficult to constrain their excitation mechanism. Their surface brightness seems to be of the same order as that of the leading bow in HH 47 D, while HH 47 D is brighter in Hα than HH 47 NE and SW. This implies that the [S II]:Hα line ratio is greater for HH 47 NE and SW than for HH 47 D, suggesting that like HH 47 D, HH 47 NE and SW are excited by shocks rather than by external ionization, consistent with the bow shock appearance of HH 47 NE. However, the signal-to-noise is rather poor in both images and there are uncertainties in the transmission curve of the [S II] filter used in the Wide Field Imager. Thus we cannot yet exclude the possibility that part of the excitation is due to external irradiation, as recently found for some jets in Orion (Reipurth et al. 1998a). This would not be an unreasonable finding, since HH 47 NE and SW are located in the Gum Nebula H II region and thus very likely exposed to the ionizing radiation of stars including ζ Pup and γ^2 Vel responsible for exciting the H II region. Clearly, spectroscopic observations are required to address the excitation mechanism of HH 47 NE and SW directly.

In summary, we have found two groups of Herbig-Haro type features, HH 47 NE and HH 47 SW, which appear to delineate the flow driven by HH 47 IRS over a significantly greater length than previously suspected ($\sim$3 pc), increasing the dynamical age of the system to $\sim$9000 years. The positions of HH 47 NE and SW with respect to the driving source and the inner jet confirm that there have been long-term secular changes in flow direction.

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